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Can Soil-friendly Nematicides Cost-Effectively Replace Soil Fumigation? Evidence from Florida Tomato Production

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Abstract. **Florida leads fresh tomato production in the United States and supplies most domestic tomatoes from October to June. However, tomato growers in Florida face persistent pest pressure, particularly from nematodes, and rely heavily on soil fumigation for control. While effective, traditional fumigation negatively affects soil health. Combined with the phase-out of methyl bromide (MBr), this has increased efforts to search for more soil-friendly alternatives, such as new nonfumigant nematicides. By applying a partial budget analysis that accounted for both revenue and cost changes, this study evaluated whether soil-friendly nematicides can be an economical substitute for fumigation in Florida tomato production. The findings showed that nonfumigant nematicide treatments were less cost-effective than fumigation and cannot replace fumigation under current conditions. Nonetheless, they are more effective for improving net returns in spring than in fall. Without supportive government policies, growers have no financial incentive to adopt these more sustainable practices. These results highlight the need for continued research to develop more cost-effective nonfumigant nematicides and suggest a potential role for supportive policy interventions. It is worth noting that this farm-level financial analysis did not capture the long-term soil health and broader environmental benefits of reducing fumigation, which are worth exploring in future studies.**

Florida, which is the largest fresh tomato-producing state in the United States, supplies nearly all the fresh market tomatoes produced domestically from October through June (>50% year-round) (Huang et al. 2022; US Department of Agriculture, National Agricultural Statistics Service 2025). This dominance is largely attributable to its year-round warm climate, including during the winter months. However, the warm and humid environment also results in some of the highest pest and disease pressures in the country (Li et al. 2025). These crop diseases and pests combined with labor shortages and increasing foreign competition have contributed significantly to the decline of Florida's tomato production (Cao et al. 2019; Li et al. 2022). Between 2000 and 2024, Florida's fresh tomato production decreased by 60% (from 1.58 billion pounds to 0.63 billion pounds) (Fig. 1). During the same period, imports of fresh tomatoes from Mexico quadrupled, soaring from approximately 1.30 billion pounds to 4.24 billion pounds (Fig. 1). Because of overlapping harvest seasons, Florida fresh tomato production faces direct competition from Mexico (Huang et al. 2022).

Plant-parasitic nematodes are among the most challenging issues in pest management, particularly because of their resilience against chemical treatments and ability to persist in soil for extended periods once established. They pose a serious threat to agriculture, with estimated annual crop losses exceeding $100 billion globally (Chitwood 2003; Forghani and Hajihassani 2020; Thoden et al. 2011). Of all the nematodes, root-knot nematodes (RKNs; *Meloidogyne* spp.) are the most damaging to tomato crops in Florida because of the year-round warm climate and sandy soil conditions (Riva et al. 2025). Infestation by RKNs results in detrimental effects such as premature wilting, stunted growth, and yellowing leaves, which ultimately lead to a substantial decline in yield. In severe cases, tomato yield reductions can range from 25% to 100% (Seid et al. 2015).

To manage nematodes effectively and economically, Florida growers have long relied on soil fumigation as the commercial standard practice because of its broad-spectrum control of nematodes, pathogens, and weeds (Cai et al. 2024; Seid et al. 2015). Studies showed that fumigation consistently increases yields, especially when combined with resistant cultivars and nonfumigant nematicides (Desaeger et al. 2017; Grabau et al. 2021; Regmi and Desaeger 2020). However, the broad action of fumigation also harms beneficial soil microorganisms, thus raising concerns about long-term soil health and sustainability (Li et al. 2022). Fumigation can also cause a "rebound effect" whereby pathogens gradually resurrect over time (Hills et al. 2020). As awareness of environmental impacts grows (Liu et al. 2025), more environmentally friendly alternatives such as biological control (Watson et al. 2020; Xiang et al. 2018), natural compounds (Wen et al. 2019), ozonated water (Zheng et al. 2020), and steam heat and solarization (Kokalis-Burelle et al. 2016) have been explored. New-generation nematicides have shown promise as safer options, thus demonstrating the ability to reduce nematode populations (Bui and Desaeger 2023, 2025; Desaeger and Bui 2021).

Building on biological literature in the area, this study evaluated whether these soil-friendly nematicides can serve as cost-effective substitutes for traditional fumigation, which is effective but raises concerns about long-term soil health, in Florida tomato production. This work accounts for key economic factors, including costs and profitability. By incorporating both yield outcomes and economic measures such as treatment costs and market prices, the findings highlight that, under current conditions, nonfumigant nematicides are not yet an economically viable replacement for fumigation. The results also reveal a clear seasonal pattern, with soil-friendly nematicides proving more effective at boosting net returns in the spring rather than in the fall. This research underscores the need for more research to develop cost-effective solutions at the farm level,

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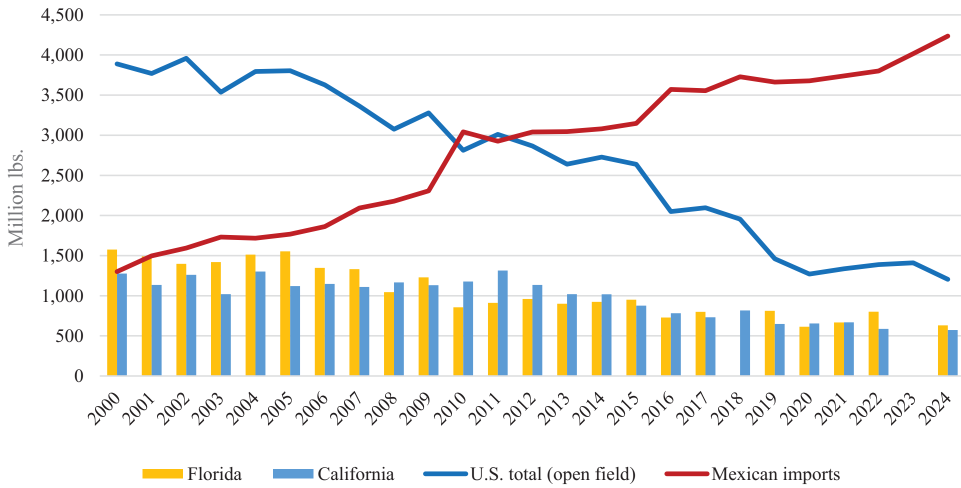

Fig. 1. Fresh tomato domestic production and imports from Mexico. Fresh tomato production data for Florida in 2018 and 2023 and California in 2023 are undisclosed from the US Department of Agriculture. Source: US Department of Agriculture, National Agricultural Statistics Service (2025). Data were compiled by the authors.

long-term analyses to assess whether improved soil health can lead to lasting farm-level benefits, and supportive government policies to encourage environmentally friendly practices.

Materials and Methods

Trial data. The data for this study were generated from small-plot field experiments conducted at the University of Florida's Gulf Coast Research and Education Center (GCREC) in Wimauma, FL, USA, over six growing seasons from Fall 2018 to Winter 2020, resulting in a total of 496 observations. The soil at GCREC is classified as Myakka fine sand (sandy, siliceous hyperthermic oxyaquic Alorthod) consisting of 96% sand, 3% silt, and 1% clay, with a pH of 7.6 and 0.8% organic matter. Fields at the GCREC were naturally infested with RKNs, providing a realistic setting for treatment evaluation.

In all experiments, the RKN-susceptible tomato cultivar HM1823 was planted on commercial-style raised beds covered with plastic mulch. The tomato cultivar HM1823 is known for its resistance to *Verticillium wilt*, *Fusarium wilt* (races 1, 2, and 3), *Fusarium crown* and root rot, Tobacco mosaic virus, and *Stemphylium*, and its intermediate resistance to *Sclerotinia sclerotiorum* (Cornell University 2025; Plant Answers 2017; University of Florida Institute of Food and Agricultural Sciences 2015). The experiment followed a split-plot design with fumigant treatments assigned to the main plots (400-ft-long × 2.5-ft-wide rows). Within each main plot (T1 bed), nonfumigant nematicide treatments were arranged in subplots using a completely randomized design (Appendix Table A1). Each trial consisted of four or nine beds that each had a length of 400 ft and width of 2.5 ft and were equipped with two drip tapes per bed (12-inch emitter spacing, 0.24 gal/h/emitter). There were two (Spring and Fall 2018) to three replicates (Spring and Fall 2019 and Spring and Fall 2020) for each treatment.

The entire bed was fumigated 1 month before transplanting (Appendix Table A1). The following two fumigant treatments were applied: (1) 100% chloropicrin (Pic100®; TriEst Ag, Greenville, NC, USA) at 200 pounds per acre and (2) a mixture of 1,3-D and chloropicrin (PicClor60®; 60% chloropicrin, 40% 1,3-Dichloropropene; TriEst Ag) at 150 pounds per acre. Fertilizer (NPK 20–20–20) was applied in the bed the same day before covering with totally impermeable film (TIF; Total Blocked; Berry Plastics Corporation, Evansville, IN, USA).

Nonfumigant nematicides were applied soon before or at planting, with plots arranged in a completely randomized block design within each main bed (Appendix Table A2). Nematicide drip applications were performed

Table 1. Summary statistics of the trials.

Season	Treatment	Mean (lb per plot)	Plot width	Plot length	Plot per acre	Yield (lb per acre)
Spring 2018	Control	105.08	27	5	322.67	33,905.07
	FuOnly	114.98	27	5	322.67	37,100.40
	NeOnly	108.90	27	5	322.67	35,138.17
	FuNe	129.49	27	5	322.67	41,782.02
Fall 2018	Control	78.67	27	5	322.67	25,384.79
	FuOnly	87.62	27	5	322.67	28,272.90
	NeOnly	66.54	27	5	322.67	21,471.31
	FuNe	93.19	27	5	322.67	30,069.91
Spring 2019	Control	91.53	22	5	396.00	36,245.28
	FuOnly	89.87	22	5	396.00	35,586.87
	NeOnly	135.08	22	5	396.00	53,493.11
	FuNe	127.33	22	5	396.00	50,422.14
Fall 2019	Control	52.40	22	5	396.00	20,751.91
	FuOnly	86.38	22	5	396.00	34,205.30
	NeOnly	83.84	22	5	396.00	33,199.37
	FuNe	80.63	22	5	396.00	31,930.43
Spring 2020	Control	97.37	19	5	458.53	44,647.04
	FuOnly	109.50	19	5	458.53	50,206.86
	NeOnly	97.97	19	5	458.53	44,920.35
	FuNe	100.72	19	5	458.53	46,182.07
Fall 2020	Control	32.22	19	5	458.53	14,775.64
	FuOnly	60.65	19	5	458.53	27,807.52
	NeOnly	33.68	19	5	458.53	15,444.32
	FuNe	63.16	19	5	458.53	28,960.48

The control represents tomato production without the application of fumigants or nonfumigant nematicides. FuOnly denotes the sole application of fumigants. NeOnly represents the exclusive use of nonfumigant nematicides. FuNe denotes a combination of fumigant and nonfumigant nematicides. "FuOnly" denotes plots treated solely with fumigants, specifically either 100% chloropicrin (Pic100®; TriEst Ag, Greenville, NC, USA) or a 1,3-D + chloropicrin mixture (PicClor60®; TriEst Ag, Greenville, NC, USA). "NeOnly" refers to plots treated exclusively with non-fumigant nematicides, including fluensulfone (Nimitz®; 40% a.i., ADAMA, Raleigh, NC, USA), fluopyram (Velum® Prime; 40% a.i, Bayer CropScience, Research Triangle Park, NC, USA), fluazaindolizine (Salibro™; 50% a.i., Corteva Agriscience, Indianapolis, IN, USA), oxamyl (Vydate® L; 24% a.i., Corteva Agriscience, Indianapolis, IN, USA), heat-killed Burkholderia (Majestene®; ProFarm Group, Inc., Davis, CA, USA), Purpureocillium lilacinum (MeloCon® WG; Certis Biologicals, Columbia, MD, USA), and thyme oil (PROMAX®; Huma, Inc., Gilbert, AZ, USA). See details in Appendix Tables A1 and A2, which provide the full list of products, rates, and timings.

Table 2. Summary statistics of the price and cost data.

Variable	Season	Time	2018 (cost per lb)	2019 (cost per lb)	2020 (cost per lb)
Price	Spring	May week 3	0.56	0.46	0.92
		May week 4	0.64	0.46	0.72
		June week 1	0.56	0.42	0.72
		June week 2	0.52	0.54	0.64
		June week 3	0.52	0.60	0.60
		June week 4	0.66	0.60	0.60
		Average	0.57	0.51	0.70
	Fall	November week 3	0.88	0.52	0.96
		November week 4	1.04	0.52	0.72
		December week 1	0.92	0.80	0.56
		December week 2	0.84	1.08	0.52
		Average	0.92	0.73	0.69
Cost	FuOnly		1,551	1,590	1,510
	NeOnly		831	851	808
	FuNe		2,381	2,441	2,319

The control represents tomato production without the application of fumigants or nonfumigant nematicides. FuOnly denotes the sole application of fumigants. NeOnly represents the exclusive use of nonfumigant nematicides. FuNe denotes a combination of fumigant and nonfumigant nematicides. "FuOnly" denotes plots treated solely with fumigants, specifically either 100% chloropicrin (Pic100®; TriEst Ag, Greenville, NC, USA) or a 1,3-D + chloropicrin mixture (PicClor60®; TriEst Ag, Greenville, NC, USA). "NeOnly" refers to plots treated exclusively with non-fumigant nematicides, including fluensulfone (Nimitz®; 40% a.i., ADAMA, Raleigh, NC, USA), fluopyram (Velum® Prime; 40% a.i, Bayer CropScience, Research Triangle Park, NC, USA), fluazaindolizine (Salibro™; 50% a.i., Corteva Agriscience, Indianapolis, IN, USA), oxamyl (Vydate® L; 24% a.i., Corteva Agriscience, Indianapolis, IN, USA), heat-killed Burkholderia (Majestene®; ProFarm Group, Inc., Davis, CA, USA), Purpureocillium lilacinum (MeloCon® WG; Certis Biologicals, Columbia, MD, USA), and thyme oil (PROMAX®; Huma, Inc., Gilbert, AZ, USA). Detailed product information is provided in Appendix Tables A1 and A2.

using two tanks pressurized with CO_2, one with water (5 gallons) and the other with a water–chemical mixture (3 gallons). The drip lines were first primed with 1 gallon of water, followed by injection of the nematicide solution, and then flushed with the remaining 4 gallons of water. The injection process required approximately 30 min, followed by an additional 2-h water application to facilitate deeper movement of the nematicide within the soil beds.

In all experiments, tomatoes were harvested at 10, 12, and 14 weeks after planting. The total yield per plot was the combined amount from these three harvests. Only marketable, healthy, large or extralarge fruits were considered. Table 1 lists the descriptive statistics for tomato yields under the various treatments from Spring 2018 to Fall 2020. Yields were converted from pounds per plot to pounds per acre to make a more intuitive cross-period comparison.

Market price data and cost data. Price data were collected from the US Department of Agriculture, Agricultural Marketing Service. We used shipping point prices for Central and South Florida tomatoes from 2018–20 to calculate sales revenue. The specific cultivar analyzed was Mature Green, which is the most widely grown cultivar in Florida. The quality grade considered was 85% US number 1 grade or better. Additionally, the size of the tomatoes was 6 × 6 packaged in 25-pound cartons. Average shipping point prices per pound on the harvest dates were adopted to measure the tomato market price. According to Table 2, the average prices per pound during the harvests in Spring 2018, Spring 2019, and Spring 2020 were $0.57, $0.51, and $0.70, respectively. For the fall harvests in those same years, the corresponding average prices were $0.92, $0.73, and $0.69 per pound.

Table 2 also lists the cost data, which were calculated as additional labor, machinery, and material expenses for fumigation and nonfumigant nematicide applications. All cost figures were adjusted for inflation using inflation factors derived from the Producer Price Index (US Bureau of Labor Statistics 2025). The estimated additional costs of fumigation were $1551, $1590, and $1510 per acre relative to the control group in 2018, 2019, and 2020, respectively. For nonfumigant nematicide applications, the added costs were $831, $851, and $808 per acre for the corresponding years (Li et al. 2025). Therefore, the combined treatment of fumigants and nonfumigant nematicides incurred total additional costs of $2381 per acre in 2018, $2441 per acre in 2019, and $2319 per acre in 2020, relative to the control group.

Statistical analysis of yield. We analyzed the seasonal yield data using an analysis of variance to evaluate treatment effects following the approach of Soto-Caro et al. (2023). The analysis was conducted using the "*agricolae*" package in R Statistical Software. Tukey's honestly significant difference (HSD) test was applied to compare treatment means using the "*HSD.test()*" function within the same package.

Partial budget analysis. A partial budget analysis, which is a tool that is widely used to assess the financial impact of changes in agricultural production techniques, has been applied in numerous studies (Cai et al. 2024; Cao et al. 2019; Nian et al. 2022). This method assesses the net economic effect of a treatment by comparing its additional costs and returns to those of a control group (Cao et al. 2019). In this context, the control was denoted as tomato production without the use of fumigants or nonfumigant nematicides. We evaluated three categories of treatments against this control group: (1) sole fumigation; (2) sole nonfumigant nematicides; and (3) a combination of fumigant and nonfumigant nematicides. The implementation of any treatment could lead to both positive and negative financial outcomes. Potential benefits might include increased revenues or reduced costs, while potential drawbacks might involve higher input costs or diminished revenues.

In this case, we included only the revenues from tomato production and the variable costs associated with fumigant nematicide and nonfumigant nematicide applications that differed between the control and treatment groups. Other costs, such as planting, land rent, and asset depreciation, that were fixed across the control and treatment groups were canceled out in a partial budget analysis (Cao et al. 2019). The revenues of tomato production were calculated using market prices, specifically the shipping point prices for Central and South Florida. Following the methodology of Cao et al. (2019) and Wade et al. (2020), we used the following equations to calculate the net effects of each treatment:

$$\textit{Net effects } (\$/acre) = \textit{Total positive effects} - \textit{Total negative effects} \quad [1]$$

$$\textit{Total positive effects } (\$/acre) = \textit{Added revenues} + \textit{Reduced costs} \quad [2]$$

$$\textit{Total negative effects } (\$/acre) = \textit{Added costs} + \textit{Reduced revenues} \quad [3]$$

We calculated the difference in gross revenues between each treatment and the control. If a treatment resulted in higher tomato yields compared with those of the control, then the value of additional yield was considered added revenues; however, if yields were lower, then it was classified as reduced revenues. Changes in costs, whether reductions or additions, accounted for differences in labor costs, machinery costs, material costs, as well as harvest and marketing expenses associated with the corresponding increase or decrease in yield.

Sensitivity analysis. A sensitivity analysis is commonly used to assess net returns and accounts for fluctuating input and output prices caused by market dynamics and policy shocks (Liu et al. 2024; Saltelli et al. 2019). A combination of lower tomato prices and higher fumigant and nonfumigant nematicide costs could substantially reduce net returns, while higher tomato prices and lower input costs could enhance returns. To account for these possibilities, we conducted sensitivity analyses that considered the variations in both prices and costs. In addition to using a single and current market price, we further considered scenarios in which the price varied by ±10%, ±20%, and ±30%. Similarly, we assessed the impact of fumigant and

Table 3. Average yields with Tukey's honestly significant difference (HSD) test results.

	Avg yield (lb per acre)				
Season	Control	FuOnly	NeOnly	FuNe	Season Avg
Spring 2018	33,905 b	37,100 ab	35,138 ab	41,782 a	36,981 c
Fall 2018	25,385 ab	28,273 ab	21,471 b	30,070 a	26,177 d
Spring 2019	36,245 a	35,587 a	53,493 a	50,422 a	53,063 a
Fall 2019	20,752 a	34,205 a	33,199 a	31,930 a	32,112 c
Spring 2020	44,647 a	50,207 a	44,920 a	46,182 a	46,021 b
Fall 2020	14,776 b	27,808 a	15,444 b	28,960 a	24,356 d
Treatment average	31,009 b	37,413 ab	33,812 b	38,644 a	

Values within the same season that are followed by the same letter are not significantly different based on Tukey's HSD test ($\alpha = 0.05$). Values for different seasons that are followed by the same letter are not significantly different based on Tukey's HSD test ($\alpha = 0.05$). The control represents tomato production without the application of fumigants or nonfumigant nematicides. FuOnly denotes the sole application of fumigants. NeOnly represents the exclusive use of nonfumigant nematicides. FuNe denotes a combination of fumigant and nonfumigant nematicides. "FuOnly" denotes plots treated solely with fumigants, specifically either 100% chloropicrin (Pic100®; TriEst Ag, Greenville, NC, USA) or a 1,3-D + chloropicrin mixture (PicClor60®; TriEst Ag, Greenville, NC, USA). "NeOnly" refers to plots treated exclusively with non-fumigant nematicides, including fluensulfone (Nimitz®; 40% a.i., ADAMA, Raleigh, NC, USA), fluopyram (Velum® Prime; 40% a.i, Bayer CropScience, Research Triangle Park, NC, USA), fluazaindolizine (Salibro™; 50% a.i., Corteva Agriscience, Indianapolis, IN, USA), oxamyl (Vydate® L; 24% a.i., Corteva Agriscience, Indianapolis, IN, USA), heat-killed Burkholderia (Majestene®; ProFarm Group, Inc., Davis, CA, USA), Purpureocillium lilacinum (MeloCon® WG; Certis Biologicals, Columbia, MD, USA), and thyme oil (PROMAX®; Huma, Inc., Gilbert, AZ, USA). Detailed product information is provided in Appendix Tables A1 and A2.

nonfumigant nematicide cost fluctuations within a range of −30% to +30% relative to the current cost levels. These analyses allowed us to estimate how changes in market conditions would influence the cost-effectiveness of each treatment.

Results

Yields of tomato production. During each harvest season, the effectiveness of different treatments was evaluated (Table 3). In Spring 2018, the combination of fumigant and nonfumigant nematicides produced the highest average marketable yield at 41,782 pounds per acre, which was an increase of 23% over the control and statistically different from that of the control group. The sole fumigation group followed with an average yield of 37,100 pounds per acre (a 9% increase), and the sole nonfumigant nematicides group yielded 35,138 pounds per acre (a 4% increase); however, neither was statistically different from that of the control group. The control group yielded an average of 33,905 pounds per acre.

In Spring 2019, the sole nonfumigant nematicide treatment emerged as the most effective and achieved an average marketable yield of 53,493 pounds per acre, which was a notable 48% increase over the control group. This was followed by the combination treatment, which yielded 50,422 pounds per acre (a 39% increase). In contrast, the sole fumigant treatment resulted in a slight 2% decrease compared with that of the control group. However, none of these three treatments produced yields that were statistically different from that of the control group.

Finally, in Spring 2020, the sole fumigant treatment achieved the highest average marketable yield at 50,207 pounds per acre, representing a 12% increase over the control yield of 44,647 pounds per acre. The combination treatment yielded 46,182 pounds per acre (a 3% increase), while the sole nonfumigant nematicide treatment yielded 44,920 pounds per acre (a 1% increase). Similar to the previous year, none of the differences in yield were statistically significant when compared with the control group.

In this study, fumigation consistently contributed to relatively high average marketable yields during the fall seasons. In Fall 2018, the combination of fumigant and nonfumigant nematicide treatment produced the highest average marketable yield at 30,070 pounds per acre, which was an 18% increase over that of the control group. This yield was statistically different from that of the sole nonfumigant nematicides group, but not significantly different from that of the other two groups. The sole fumigant treatment followed, with a yield of 28,273 pounds per acre (an 11% increase over that of the control). In contrast, the sole nonfumigant nematicides group experienced a 15% decrease in yield compared with that of the control group, producing just 21,471 pounds per acre. Overall, the yield differences among the three treatments were not statistically significant.

Remarkably, in Fall 2019, all treatment groups showed a substantial surge in average marketable yields compared with that of the control group, which yielded 20,752 pounds per acre. The sole fumigation group recorded a 65% increase, the sole nonfumigant nematicides group recorded a 60% increase, and the combination treatment group recorded a 54% increase. However, these numbers were not statistically different.

In Fall 2020, the ranking of treatment effectiveness mirrored that of Fall 2018. The combination treatment produced the highest yield at 28,960 pounds per acre (a 96% increase over that of the control), followed by the sole fumigation group at 27,808 pounds per acre (an 88% increase over that of the control) and the sole nonfumigant nematicides group at 15,444 pounds per acre (a 5% increase over that of the control). Statistically, the yield from the combination treatment was not significantly different from that of the sole fumigation group, but it was significantly higher than the yields of both the sole nonfumigant nematicides group and the control group.

As shown in Table 4, the analysis of variance results indicated that the treatment, season, and treatment × season interaction all had statistically significant impacts on the tomato yield. Regarding the treatment factor, $F = 6.837$ and $P = 0.000163$ were observed, suggesting a statistically significant effect on yield. Regarding the season factor, $F = 66.115$ and $P < 2\text{e-}16$ were observed, indicating a very strong and highly statistically significant seasonal effect. Regarding the treatment × season interaction, $F = 1.557$ and $P = 0.081951$ were observed. Although this P value was above the conventional 0.05 threshold, it suggested a marginally significant interaction effect on yield.

Profitability analysis. To determine the most cost-effective treatment option for tomato cultivation, we conducted a partial budget analysis. This approach involved calculating the estimated treatment costs and corresponding revenues (Table 5). The additional costs incurred by the treated groups were primarily driven by labor, materials, and equipment required for applying fumigants and nonfumigant nematicides. From 2018–20, the estimated added costs per acre were $1551, $1590, and $1510 for fumigation, $831, $851, and $808 for nonfumigant nematicides, and $2381, $2441, and $2319 for the combined treatment, respectively (Li et al. 2025).

The added revenues were determined based on yield and price increases and were calculated by multiplying the yield difference relative to the control group by the corresponding market price of tomatoes. We then examined the negative, positive, and net effects of each treatment in comparison with the control group using the calculation methods shown in Eqs. [1] to [3]. It is worth noting that although most treated groups exhibited higher average yields and revenues than those of the control group, the net differences in total economic effect were not uniformly consistent. These variances suggested that these treatments might either

Table 4. Analysis of variance results for yields.

	Degrees of freedom	Sum Sq	Mean Sq	F value	P (>F)
Treatment	3	3.30E+09	1.10E+09	6.837	0.000163***
Season	5	5.32E+10	1.06E+10	66.115	<2e-16***
Treatment × season	15	3.76E+09	2.51E+08	1.557	0.081951*

*, **, and *** Significance at 10%, 5%, and 1%, respectively.

Table 5. Cost-effectiveness analysis of different treatments relative to the control group.

Year	Season	Treatment	Added revenues (cost per acre)	Reduced costs (cost per acre)	Total positive effects (cost per acre)	Added costs (cost per acre)	Reduced revenues (cost per acre)	Total negative effects (cost per acre)	Net effects (cost per acre)
2018	Spring	FuOnly	1,836	0	1,836	1,551	0	1,551	285
		NeOnly	709	0	709	831	0	831	−122
		FuNe	4,527	0	4,527	2,381	0	2,381	2,145
2018	Fall	FuOnly	2,651	0	2,651	1,551	0	1,551	1,100
		NeOnly	0	0	0	831	3,593	4,423	−4,423
		FuNe	4,301	0	4,301	2,381	0	2,381	1,920
2019	Spring	FuOnly	0	0	0	1,590	337	1,926	−1,926
		NeOnly	8,819	0	8,819	851	0	851	7,968
		FuNe	7,249	0	7,249	2,441	0	2,441	4,809
2019	Fall	FuOnly	9,794	0	9,794	1,590	0	1,590	8,205
		NeOnly	9,062	0	9,062	851	0	851	8,211
		FuNe	8,138	0	8,138	2,441	0	2,441	5,697
2020	Spring	FuOnly	3,881	0	3,881	1,510	0	1,510	2,371
		NeOnly	191	0	191	808	0	808	−618
		FuNe	1,071	0	1,071	2,318	0	2,318	−1,247
2020	Fall	FuOnly	8,966	0	8,966	1,510	0	1,510	7,456
		NeOnly	460	0	460	808	0	808	−348
		FuNe	9,759	0	9,759	2,318	0	2,318	7,441

The control represents tomato production without the application of fumigants or nonfumigant nematicides. FuOnly denotes the sole application of fumigants. NeOnly represents the exclusive use of nonfumigant nematicides. FuNe denotes a combination of fumigant and nonfumigant nematicides. "FuOnly" denotes plots treated solely with fumigants, specifically either 100% chloropicrin (Pic100®; TriEst Ag, Greenville, NC, USA) or a 1,3-D + chloropicrin mixture (PicClor60®; TriEst Ag, Greenville, NC, USA). "NeOnly" refers to plots treated exclusively with non-fumigant nematicides, including fluensulfone (Nimitz®; 40% a.i., ADAMA, Raleigh, NC, USA), fluopyram (Velum® Prime; 40% a.i, Bayer CropScience, Research Triangle Park, NC, USA), fluazaindolizine (Salibro™; 50% a.i., Corteva Agriscience, Indianapolis, IN, USA), oxamyl (Vydate® L; 24% a.i., Corteva Agriscience, Indianapolis, IN, USA), heat-killed Burkholderia (Majestene®; ProFarm Group, Inc., Davis, CA, USA), Purpureocillium lilacinum (MeloCon® WG; Certis Biologicals, Columbia, MD, USA), and thyme oil (PROMAX®; Huma, Inc., Gilbert, AZ, USA). Detailed product information is provided in Appendix Tables A1 and A2.

enhance or hinder the profitability of tomato production. The outcome under different treatments may vary depending on several factors, including the magnitude of the yield gap between treated and control groups, prevailing market prices, and costs associated with implementing each treatment.

The results varied across spring seasons, and none of the three treatments consistently proved to be the most cost-effective. In Spring 2018, the combination of fumigant and nonfumigant nematicide treatment was the most cost-effective option, generating a profit of $2145 per acre relative to that of the control group, followed by sole fumigation treatment ($285 per acre). In contrast, the sole nonfumigant nematicides treatment resulted in a slight loss of $122 per acre. However, the situation reversed in Spring 2019. The sole nonfumigant nematicides group emerged as the most cost-effective and contributed to the largest net effect ($7968 per acre), followed by the combination of fumigant and nonfumigant nematicides treatment ($4809 per acre). Notably, the sole fumigation treatment surprisingly resulted in a substantial loss of $1926 per acre. In Spring 2020, the sole fumigation treatment demonstrated the best performance, with a net gain of $2371 per acre. Both the combination of fumigant and nonfumigant nematicide treatment and the sole nonfumigant nematicides treatment led to negative net effects, estimated at −$1247 per acre and −$618 per acre, respectively.

Fumigated soil proved to be both cost-effective and indispensable during the fall seasons. Nonfumigated treatment incurred considerable negative net effects, with losses of $4423 per acre in Fall 2018 and $348 per acre in Fall 2020. Conversely, fumigated treatments, whether applied alone or in combination with nonfumigant nematicides, consistently generated high positive net effects in Fall 2018, Fall 2019, and Fall 2020. In Fall 2018, the combination treatment yielded a profit increase of $1920 per acre, while the sole fumigation treatment resulted in a gain of $1100 per acre relative to that of the control. In Fall 2019, net effects increased sharply to $5697 per acre for the combination treatment and $8205 per acre for the fumigation-only treatment. Interestingly, the sole nonfumigant nematicide treatment slightly outperformed the combination treatment that year, with a net gain of $8211 per acre. By Fall 2020, the sole fumigation treatment remained the most cost-effective, producing a net return of $7456 per acre, closely followed by the combination treatment ($7441 per acre).

Our results suggested that, in the fall, fumigation treatments, whether applied alone or in combination with nonfumigant nematicides, consistently outperformed the control in terms of cost-effectiveness. Specifically, fumigation alone yielded an average increase in returns of $5587 per acre, while the combination treatment led to an average increase of $5019 per acre compared with plots without fumigation. They also suggested that the application of nonfumigant nematicides was more beneficial in the spring, resulting in an average return increase of $2410 per acre compared with plots without nonfumigant nematicides. However, the benefit was notably smaller in the fall, with an average return increase of only $1146 per acre. The reduced effectiveness of sole nonfumigant nematicides treatments in the fall may be attributed to Florida's high soil temperatures and humidity during that season, which create favorable conditions not only for nematodes but also for a broader range of soilborne pests. This may explain why omitting fumigation in the fall leads to greater yield losses. Overall, our findings suggest that current nonfumigant nematicides are not sufficient substitutes for fumigation. Further research and development are needed to improve their efficacy and economic viability as alternatives to traditional fumigation methods.

Sensitivity analysis. To evaluate the impact of evolving market conditions on treatment outcomes, we conducted a series of sensitivity analyses. Initially, to assess the effect of tomato market price fluctuations and cost variations on the total treatment effect, we considered a combination of ±10%, ±20%, and ±30% variations from the baseline (Appendix Tables A3 and A4). The results showed that increases in market prices proportionally amplified the economic gains from yield improvements, thereby enhancing the profitability of all treatment groups (Appendix Tables A5-A7). Conversely, declines in market prices diminished the economic benefits of yield gains, making treated tomatoes less profitable. Importantly, when treatments resulted in yield losses, the increase in tomato market price would further amplify the economic losses, while the decline in price would reduce the losses. For example, under a 30% increase in the market price, increasing it to $1.19 per acre in Fall 2018, the sole nonfumigant nematicides group suffered from an additional 30% loss, with total losses ranging from $5750 per acre to $5252 per acre. Similarly, the increase (or decrease) in fumigant and nonfumigant nematicides cost had a significant positive (or negative) impact on tomato net profit for all treatment groups. Therefore, both the market price of tomatoes and the cost of treatments directly influence the profitability of tomato treatment strategies.

In terms of the choice of treatments, fumigated treatments remained the most cost-effective strategy in most fall seasons. However, in Fall 2019, the combination of declining prices and increasing input costs shifted the most profitable option from the sole fumigation to the sole nonfumigant nematicides treatment. Likewise, in Fall 2020, when treatment costs decreased and market prices increased by 10% or more, combining fumigation with nonfumigant nematicides became the most advantageous strategy. Conversely, a 10% or greater increase in treatment costs combined with a 10% or greater decrease in price favored the omission of nonfumigant nematicides in fumigated soils. In the spring seasons, the basic conclusion remained the same.

Discussion and Conclusions

This study examined whether more environmentally friendly alternatives, nonfumigant nematicides, can be a cost-effective substitute for traditional soil fumigation, which, despite its effectiveness against nematodes, has documented negative impacts on soil health (Grabau et al. 2021; Regmi and Desaeger 2020). By applying a partial budget analysis to six seasons of small-plot field experiments at the University of Florida's GCREC, we evaluated the farm-level economic impacts of nematode management options. The trials compared fumigants, nonfumigant nematicides, and their combinations against untreated control; yields were measured across replicates and converted to a per-acre basis. Market revenues were calculated using the US Department of Agriculture, Agricultural Marketing Service shipping point prices from 2018–20, while treatment-specific costs reflected actual input applications estimated by Li et al. (2025). This framework allowed us to quantify the net economic effects of alternative nematode controls under observed yields, prevailing prices, and realistic costs.

We found that fumigation, whether used alone or with nonfumigant nematicides, remained consistently cost-effective, especially in the fall. Although nonfumigant nematicides showed some promising results in the spring, they were still not cost-effective enough to replace fumigation in Florida tomato production. Further research and development are necessary to enhance the effectiveness and economic viability of nonfumigant nematicides as standalone alternatives. Without these future solutions and improvements, growers will not be able to adopt sustainable nematode management practices without compromising their short-term economic returns.

Our results supported the prior findings (Bui and Desaeger 2025; Grabau et al. 2021) that fumigation combined with nonfumigant nematicides can reliably improve tomato yields. However, it is worth noting that higher yields do not necessarily translate into higher profits. The profitability of treated tomato production largely depends on market tomato prices and treatment costs. For instance, in Fall 2020, lower input costs coupled with a 10% price increase made the combination of fumigant and nonfumigant nematicide treatment most cost-effective. In contrast, under conditions of higher treatment costs and a 10% price decrease, sole fumigation became the optimal choice. This reinforces the value of integrating economic modeling with agronomic field trials because it highlights the conditional profitability of each management strategy depending on market forces. Economic outcomes were sensitive not only to the treatment performances and yields but also to input price fluctuations and output market conditions.

This study, however, had several limitations. First, the yield was derived from small experimental plots, which may not fully reflect commercial-scale production outcomes. Nonetheless, the experimental design closely adhered to commercial practices, and the research fields were located near major tomato producing areas in Florida, enhancing the applicability of our findings to larger-scale operations. Nevertheless, real-world adoption may be influenced by additional logistical or behavioral factors, including grower perceptions, equipment availability, and labor capacity to implement nonfumigant protocols. Second, the analysis was based on 3 years of data, which may not have captured long-term trends or variability in treatment performance. Environmental conditions such as edaphic factors, temperature, and humidity vary across seasons and likely influence nematode pressure and treatment efficacy (Bui and Desaeger 2023; Nisa et al. 2021). For instance, nematode populations can peak under high soil moisture and moderate temperatures, but they decline during hotter, drier periods (Nisa et al. 2021). These abiotic factors, along with soil type and irrigation practices, influence both nematode activity and the distribution and efficacy of nematicides. In fact, drip-applied nematicides require uniform water coverage to work effectively, which can be challenging in coarse sandy soils (Bui and Desaeger 2023). Beyond climate and soils, other stresses may have influenced treatment responses. Nematodes often interact with soilborne pathogens, creating disease complexes that can cause more damage than either pest alone (Parrado and Quintanilla 2024). Nematode feeding also reduces water and nutrient uptake, making plants more vulnerable to drought or nutrient stress (Habteweld et al. 2024). Importantly, preplant soil fumigation suppresses a broad range of soil pests, while nonfumigated treatments leave crops more exposed to these combined pressures. Future studies should aim to gather more extensive tomato production data over a longer period to enable a thorough examination of the economic outcomes of both fumigated and nonfumigated treatments. Finally, from a sustainability perspective, although the nonfumigant nematicide treatments were selected for their soil-friendly profiles, our cost estimates did not incorporate the quantified long-term environmental impacts associated with each treatment. This may have led us to understate the full sustainability benefits of nonfumigant alternatives and overestimate the net profitability of traditional fumigation in the long run. Future research should incorporate comprehensive societal-level evaluations that explicitly quantify these environmental trade-offs. For example, long-term studies should assess how reducing fumigation can enhance soil health, productivity, and profitability over time. Metrics such as soil microbial recovery, nematode rebound effects, and downstream environmental impacts (e.g., nitrate leaching, greenhouse gas emissions) will be essential to fully capturing the balance between short-term economic returns and long-term ecological sustainability.

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